SLICEABLE BANDWIDTH VARIABLE TRANSPONDERS FOR ELASTIC OPTICAL NETWORKS: THE IDEALIST VISION

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Abstract:

This paper describes the general architecture for a sliceable bandwidth variable transponder as identified within the IDEALIST European project. The capability of generate super-channels (optical connections with several adjacent optical sub-carriers) and the slice-ability (super-channels generated together but independently routed in the network towards different destinations) are the key elements of the considered architecture.

1 Introduction

To address the issues of scalability, flexibility and end-to-end performance in next generation optical networks, research is deeply investigating the Elastic Optical Networks (EONs) paradigm as the main road in the medium term for an efficient utilization of the optical spectrum [1]. One key element in an EON is a novel class of transponders called Bandwidth Variable Transponder (BVT). BVTs are capable of providing several dynamic functionalities that can be programmed by a remote controller, such as variable coding and overhead, modulation format, symbol rate and spectral shaping. This enables to support multiple rates (e.g. from 10 Gb/s to 1 Tb/s) and to provide spectral efficiency versus reach optimization. In order to further increase flexibility, a Sliceable Bandwidth Variable Transponder (S-BVT), that is capable of generating multiple optical flows, independently routed to different destinations or/and simultaneously distributed over different portions of the optical spectrum (media-channels), is proposed [2].
This paper reports on the general architecture for an S-BVT as discussed within the European Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks (IDEALIST) project. Examples of transponder implementations employing different transmission techniques are shown, highlighting advantages, economics and possible use cases.

2 S-BVT concept

BVTs, as a special class of transponders, are able to dynamically tune the required optical bandwidth and transmission reach by adjusting their parameters such as gross bit rate, Forward Error Correction (FEC) coding, modulation format and shaping of optical spectrum. BVTs enable a trade-off between spectral efficiency and transmission reach, using spectrally efficient modulation formats (e.g., PM-8PSK, PM-16QAM, PM-64QAM) for short-reach connections, and more robust but less efficient modulation schemes (e.g. PM-QPSK, PM-BPSK) for long-haul links. The transmission bandwidth (up to a maximum value) is exclusively dedicated to a single traffic demand and adjusted in fixed steps under software control in order to be adapted to the actual traffic demand and reach. A single Optical Channel (OCh) – a single optical carrier – is generated, feeding a single media channel.
S-BVT transponders enhance BVT functionalities by being able to allocate their transmission net bandwidth into one or several independent optical flows. As a result, the optical output of an S-BVT is a group of super-channels (several spectrally adjacent optical sub-carriers routed as a single entity in the network) with different destinations and modulation formats employing different portions of the optical spectrum and media channels, efficiently feeding single or multiple add/drop ports. Thus, an S-BVT should be considered as a collection of "virtual" lower-capacity BVTs (one for each elemental sub-carrier), logically associated in groups to generate super-channels.
One way to fully exploit sliceability is to suitably distribute specific functions among electrical (digital) and optical Optical Transport Network (OTN) layers, as shown in Figure 1. Multiple traffic demands are associated with flexible OTN "Beyond 100G" Optical Transport Units (OTUC) through a Configurable/Sliceable Flexible OTN interface module capable of dynamically partitioning its total throughput into dynamically created multiple OTUCn virtual interfaces.
The same module should also be able to fragment each OTUCn among several Tributary Groups (OTUCnTG), if needed, to allow the distribution of load over different media-channels. The configurable/sliceable flexible OTN interface module feeds a variable pool of optical front end modules (including light sources, I/Q modulators, drivers and receivers, associated with the processing electronics, such as DAC, ADC, DSP, FEC coding and decoding). The S-BVT's optical front ends are named Multiflow Optical modules.
A Flow Distributor, such as an electronic switching matrix,

enables the traffic to be shared, via a multi-lane interface, among several optical sub-carriers for transmission in the optical layer by directing a suitable number of electrical lanes to each specific sub-carrier.

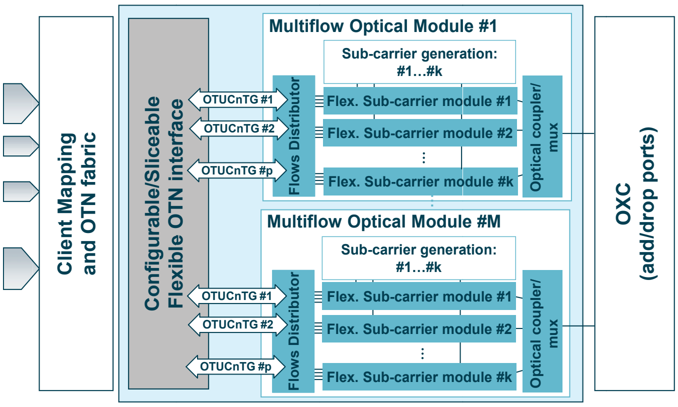

Figure 1: S-BVT architecture building blocks; OTUCnTG: "Beyond 100G" Optical Transport Unit Tributary Group of order *n* (*n* stand for *n* times 100G); OXC: Optical Cross Connect.

A modular solutions, especially at the optical front end, could be adopted to overcome high initial investments by a "pay as you grow" approach.

S-BVTs could be implemented by supporting one or more of the following transmission techniques: Nyquist Wavelength-Division Multiplexing (NWDM), Orthogonal Frequency-Division Multiplexing (OFDM), and Time-Frequency Packing (TFP) as detailed in [2]. All of them are suitable in creating a highly efficient packing of spectrally adjacent optical sub-carriers to create a high capacity (up to several 100 Gb/s) single transmission optical entity, the super-channels, to be optically routed in the EON.

An S-BVT finds application in high capacity networks whenever the transmission rate is to be adapted to the actual traffic demand by expanding or contracting the bandwidth of an optical path (e.g. varying the number of sub-carriers), by adapting the optical reach, and by directing the several generated super-channels, of different size and capacity, toward specific independent destinations. In flexible high-rate EONs, slice-ability of super-channels can also be used effectively during failure recovery procedures by overcoming capacity bottlenecks thereby enabling dynamic rearrangement of optical bandwidth.

3 OTN multiplexing architecture

As already mentioned, the S-BVT comprises a Configurable/Sliceable Flexible OTN interface module for client distribution from the OTN fabric into ODUCn/OTUCn, with a net capacity that can vary, in our example (Figure 2), from the 100 Gb/s OTU4 to a maximum of 1.2 Tb/s OTUC12, with a granularity of 100 Gb/s. Other granularities or total net capacity are obviously possible.

A rate-flexible OTU line interface, complementing the flexibility provided by ODUflex in the LO-ODU service layer, is expected to be one of the distinguishing attributes of the OTN hierarchy advancement "beyond 100 G" (B100G OTN), and therefore highly relevant here. The current predominant thinking in the OTN evolution debate is to prefer an 'n x 100 Gb/s' (with $n \geq 2$) iterative structure, termed OTUCn, meeting the need to distribute bits over multiple lanes as happens for Inter-Domain Interfaces (IrDI) or for Inverse-Multiplexing. The 100 Gb/s modularity has been chosen according to the current interim agreement in ITU-T study group 15 for "Beyond 100G" standardization evolution, although a finer granularity (i.e. 25 Gb/s) could be considered as an interesting alternative, for instance for metro-regional application.

The OTUCn frame interleaves the 'n' standard OTU4-like sub-frames. The index 'n' immediately suggests the possibility of variable bit rates in 100 Gb/s steps, with the potential to segment fat signals (e.g., 400 Gb/s or above) into multiple thinner pipes to be transported over multiple sub-carriers (their number and modulation format being the best compromise between spectral efficiency and reach), possibly fitting into a single media channel to minimize spectrum occupancy (adjacent optical sub-carriers can be closely packed with no or reduced guard-band) or alternatively into multiple, non-adjacent, media channels to deal with the possible spectral fragmentation in existing networks. Each OTUCn fragment (OTUCnTG) would in turn be inverse multiplexed into a number of discrete lanes: multiple lanes (e.g., at 28 Gb/s) drive optical modulators within the "Flex Sub-carrier module" to write data on an optical sub-carrier (e.g., at 112 Gb/s, assuming four lanes).

The S-BVT enables the total net capacity to be dynamically partitioned to serve different and independent clients at the same time. In our example (Figure 2), the S-BVT can serve from a minimum of one single client to a maximum of 12 independent clients at 100 Gb/s speed, if we assume the overall 1.2 Tb/s S-BVT capacity all dedicated to this Tera client.

The configurable/sliceable flexible OTN interface module can flexibly fragment high-data rates into lower-data streams.

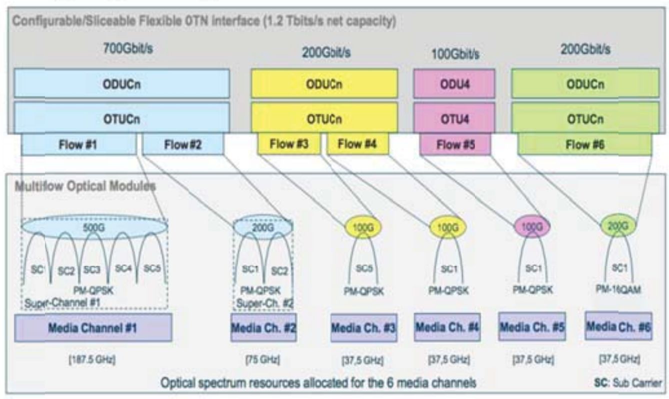

Figure 2: multiplexing architecture (1.2Tb/s net capacity is considered). ODUCn/OTUCn: "Beyond 100G" Optical Data/Transport Unit of order *n* (*n* stand for n-times 100Gb/s); SC: Optical sub-carrier.

Figure 2 reports two examples for this defragmentation: a 700 Gbit/s aggregated traffic demand (light blue in the picture) is divided by the OTN layer into two different streams (or OTUCnTGs), the first at 500 Gb/s and the second at 200 Gb/s, each one feeding two separate media channels (#1 and #2). Similarly, the traffic from an interface at 200 Gb/s (yellow blocks) is divided into two different streams, feeding respective media channels #3 and #4. Traffic could be also not fragmented as illustrated by the case of a 200 Gb/s and a 100 Gb/s flows with green and violet boxes in Figure 2.

4 Flex sub-carrier module architecture

As mentioned before, within the IDEALIST project, the Flex Sub-carrier module has been implemented focusing on three main transmission techniques: NWDM, OFDM, and TFP. The three techniques may be suitable for different scenarios (e.g., long haul or metro/regional network) and show different levels of spectral efficiency (measured with b/s/Hz) and complexity.

With NWDM transmission a pulse-shaping filter is applied at the transmitter, confining the bandwidth within the Nyquist frequency of the signal, which is half the symbol rate. This allows a dense allocation of NWDM channels. Root Raised Cosine (RRC) is a popular choice for the pulse-shaping filter. Matched RRC filters at transmitter and receiver help avoiding inter-symbol interference (ISI) due to the narrow filtering. A sharp roll–off (i.e. ≤ 0.2) is essential to reduce linear crosstalk with neighbouring channels and maximize spectral efficiency (SE).

Optical OFDM is based on the transmission of multiple orthogonal electrical sub-carriers, which can be independently modulated by different formats, yielding unique bit-rate/bandwidth scalability and spectral domain manipulation capability, with sub- and super- wavelength granularity. The orthogonal electrical sub-carriers are overlapped in the frequency domain, providing a high SE. Using a number of electrical sub-carriers equal or greater than 64, a more flexible OFDM spectrum with squared profile is obtained and the same SE as NWDM is achieved [3]. By combining coherent detection and DSP, the tolerance to transmission impairments can be significantly enhanced, achieving ultimate performance.

TFP is another transmission technique that can be implemented in the Flex Sub-carrier module. TFP consists of sending pulses that strongly overlap in time or frequency or both to maximize SE (e.g., 5.16b/s/Hz), while introducing ISI and/or inter-sub-carrier interference (ICI) among optical sub-carriers [4,5]. Coding and detection are to be properly designed to account for this. A low-density parity-check (LDPC) code can be used to approach the maximum information rate achievable with the given modulation (typically PM-QPSK), accounting for the presence of noise, ISI, ICI, etc. Such code is introduced by an encoder that can be placed in the Flex Sub-carrier module. Code rate, thus spectrum efficiency, may vary with the optical-signal-to-noise ratio (OSNR) of the sub-carrier (the lower the OSNR, the larger the redundancy). The receiver of each optical sub-carrier exploits coherent detection with DSP and given the introduced ISI, TFP a receiver based on sequence detection is required [6].

Once defined the transmission technique, the key components parameters, constituting the Multiflow Optical module, are: analogue bandwidth, effective resolution of the DAC, extinction ratio of the dual-polarization I/Q modulator and time-frequency laser stability. In order to cope with hardware and transmission limitations of off-the-shelf components, advanced DSP algorithms may be required, e.g. pre-distortion methods for the most relevant non ideal behaviour of components and for partially or totally compensating linear and nonlinear fibre propagation impairments. Moreover, authors in [7] showed that it may be beneficial from a performance point-of-view to increase the number of optical sub-carriers to cope with electronics speed limitations. However, this comes at the cost of roughly doubling the number of hardware components and associated costs.

A related component technology challenge is the integration that may provide cost reduction as well as physical dimensions reduction. High integration levels also permit better monitoring, management and control of system performance. Energy efficiency of an integrated system is a further benefit. Silicon photonics integration can help, e.g. sharing thermal control and power dissipation functions among a subset of optical sub-channels, but with current hybrid approach the contribution to total power saving would be limited to about 10%. Also hybrid integration of passive and active polymer polyboard is a promising technique [8].

To achieve significant power reduction, the more promising technology involves CMOS (e.g. a single lithographic process can integrate hundreds of photonic components with millions of transistors with significant power reduction benefits) [9].

Finally, two solutions can be adopted for the Sub-carrier generation module (Figure 1): an array of laser sources or a multi-wavelength source [10]. With the former the spectrum allocation of optical sub-carriers does not present any limitation; with the latter, other advantages may be achieved (primarily, costs and power consumption can be reduced given that on N generated sub-carriers, N-1 lasers are saved).

A modular architecture, with hot-pluggable small form-factor line side modules, should efficiently fit also the proposed S-BVT for what concerns the Multiflow Optical Module. Modules with 2 to 4 flexible sub-carriers, guarantee probably a more affordable integration level in a short time frame, and allow the network operator to purchase only the resources needed to meet just the current traffic demands over time (i.e., saving CapEx). Moreover, the cost of the same optical and electronic module, generally, decreases over time, allowing further savings. Finally new modules, with improved transmission performance might be plugged into the same S-BVT slots as soon as they will be available.

Following the general architecture of Figure 1, each Multiflow Optical Module could include optical devices to collect all modulated sub-carriers into a single optical IN/OUT port. By mixing modules, several combinations are allowed in terms of flexibility, total traffic and simultaneous use of different modulation formats for demands needing different reaches. Thus, to create a super-channel the S-BVT must guarantee that sub-carriers are at fixed and stable adjacent frequencies and "logically grouped" together even if they are generated by different modules.

Two options are then conceivable for compound signal collection.

1) An (amplified) external combiner is added to the S-BVT, collecting outputs together and feeding a single Add/Drop

port of the OXC/ROADM node. Feeding a single Add/Drop port, the super-channel is immune to filtering effects from the OXC/ROADM node [11], but it presents the drawbacks of not allowing the reuse of the same lambda within the S-BVT, and possibly requiring more optical power to overcome losses from couplers. However, in this case, a fully packed NWDM super-channel is feasible without the need of internal additional band guards.
2) Each Multiflow module feeds directly an Add/Drop port of the OXC/ROADM node. In this case, many ports are now needed in the OXC/ROADM. A super-channel consisting of more than 2 carriers (depending on the employed Multiflow modules) needs an internal band guard to reduce detrimental filtering effects in the Add/Drop node, that affect the SE and prevent the feasibility of a true NWDM super-channel. In fact, in this case, the S-BVT is actually creating several groups of packed optical sub-carriers feeding adjacent media channels.
To avoid this, a compromise hybrid solution between the two previous options is the use of Add/Drop chains employing Multicast Switches with a number of IN/OUT ports matching that of the fully-equipped S-BVT. In this case super-channels of generic size, up to the maximum allowed by the S-BVT, can be generated without introducing band guards but with the drawback of greater complexity and cost in the OXC/ROADM node. A detailed discussion of the matching between Add/Drop architecture of OXC nodes and S-BVTs optical capacity and number of ports can be found in [12]

Conclusions

Transport network evolution from current dense WDM systems towards elastic optical network, could significantly increase both transport network scalability and flexibility, by properly optimizing the available spectrum.
If innovation is not introduced quickly, the current traffic increase will soon seriously impact on both network costs and power consumption. To minimize these, optical and electrical switching nodes and their transponders should use, as much as possible, optical switching, advanced DSP algorithms, and flexibility (such as slice-ability). For these reasons the adoption of a flexible spectrum allocation grid, super-channels and S-BVTs supporting slice-ability, as well as the integration of S-BVT modules into a single platform, could be mandatory to support traffic increase and dynamicity while contain costs and power consumption.
To complete the scenario, S-BVTs can improve multi-layer restoration enabling restoration bandwidth to multiple nodes, and dynamically re-provisioning slices according to a flow request schedule.

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